ASSESSMENT METHODOLOGY FOR DIAGONALLY CRACKED REINFORCED CONCRETE DECK GIRDERS

Final Report

SPR 350
SR 500-091

RESEARCH

Oregon Department of Transportation

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by

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16. Abstract

This report details the results of a research program conducted to estimate the capacity and remaining life of 1950's vintage conventionally reinforced concrete deck girder (RCDG) bridges with diagonal cracks. The investigation encompassed field testing, laboratory testing, and analysis to develop a reliability based assessment methodology. Background, findings, and conclusions from each of these components are provided in individual sections of this report. Current limitations are described, including the impact of skew, temperature and shrinkage effects on capacity, as well as serious stem-flange interface cracking. There are also limitations in predicting the capacity of bent caps. Finally, recommendations are made for implementing the assessment methodology.

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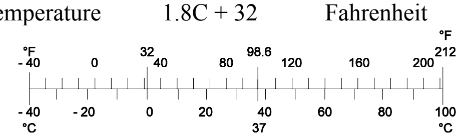
SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
In	inches	25.4	Millimeters	mm
Ft	feet	0.305	Meters	m
Yd	yards	0.914	Meters	m
Mi	miles	1.61	Kilometers	km
		AREA		
In^2	square inches	645.2	Millimeters squared	mm^2
ft^2	square feet	0.093	Meters squared	m^2
Yd^2	square yards	0.836	Meters squared	m^2
Ac	acres	0.405	Hectares	ha
Mi^2	square miles	2.59	Kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	mL
Gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	Meters cubed	m^3
Yd^3	cubic yards	0.765	Meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
Oz	ounces	28.35	Grams	g
Lb	pounds	0.454	Kilograms	kg
T	short tons (2000 lb)	0.907	Megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8C + 32	Fahrenheit	°F



* SI is the symbol for the International System of Measurement

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DISCLAIMER

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EXECUTIVE SUMMARY

This report details the results of a research program conducted to estimate the capacity and remaining life of 1950's vintage conventionally reinforced concrete deck girder (RCDG) bridges with diagonal cracks. The investigation encompassed field testing, laboratory testing, and analysis to develop a reliability based assessment methodology. Background, findings, and conclusions from each of these components are provided in individual sections of this report and are summarized here.

Field Tests

The response of three in-service bridges was monitored under ambient traffic conditions as well as controlled loading. For select girders, the stress ranges in the steel shear stirrups (the vertical steel reinforcement) and the deformation of diagonal cracks were measured while under vehicle loading. Load distribution and impact factors, key values for structural analysis, were developed from the data. Comparing the calculated factors with American Association of Highway Transportation Officials (AASHTO) design factors showed that AASHTO load distribution factors are conservative, but the AASHTO impact factor is representative of actual bridge response. Field measurements also showed that the repetitive stress cycles produced in the shear stirrups due to traffic is unlikely to cause metal fatigue (high cycle fatigue, HCF) of the stirrups.

Laboratory Tests

Laboratory tests were conducted on 44 large-scale girder elements designed to represent as near as possible 1950's construction practice. Various steel reinforcement configurations were tested to determine the effect of typical vintage beam characteristics on load capacity. Bending conditions were varied to reproduce girder behavior at different positions in a bridge. Loading protocols included incrementally increasing load amplitudes, repeated loading up to two million cycles, and a moving load along the length of the girders. The following are the key results:

- Adequate anchorage of flexural steel reinforcement (the horizontal steel reinforcement) so that the steel bars did not slip in the concrete was crucial to achieve higher ultimate capacity. If the flexural steel terminates before the end of the girder, which was a common practice in the 1950s, diagonal cracks are likely to extend into the beam from this area, and the crack will not be as well constrained to carry load resulting in decreased ultimate load capacity.

- Initial crack damage may not necessarily contribute to the final failure mode if loading conditions change so as to create a new critical region.

- Crack width alone may not indicate the level of previous damage to the beam. Tightly spaced stirrups exhibited relatively small crack width at failure while widely spaced stirrups exhibited large and wider cracks at failure.

- Cyclic loading to cause stress in the specimen stirrups equivalent to the single highest stress measured during field testing verified that HCF of the steel is unlikely.

- Cyclic loading was applied to cause progressive permanent deformation of the shear stirrups (low cycle fatigue, LCF), bond deterioration between the stirrups and concrete, increased crack width, stirrup fracture, and ultimately element failure. However, specimens were able to sustain large numbers of LCF cycles; consequently, traffic loading is unlikely to produce the LCF failures observed in the laboratory on actual bridges.

- Though metal fracture of the stirrups due to HCF was shown to be inconsequential, fatigue of the bond between the concrete and the stirrups was also investigated. Debonding could produce less constraint at diagonal crack locations and reduced capacity. However, specimens fabricated with fully debonded stirrups exhibited only slightly reduced capacity than otherwise similar specimens with bonded stirrups.

- Conventional laboratory load testing uses stationary loading points, though bridges are exposed to loads moving along the length of the girders. A set of moving load tests produced similar capacity measurements as comparable stationary tests, verifying that the stationary tests reflect the behavior of in-service girders.

Analysis

Five analysis methods were compared for estimating the shear capacity of the laboratory specimens: ACI method; *Response 2000*™, a specialty analysis program; AASHTO Modified Compression Field Theory (MCFT); Strut-and-Tie Method; and finite element method. Over the range of variables considered, AASHTO-MCFT and *Response 2000*™, which both rely on MCFT, reasonably estimated the capacity of the specimens, including cases with very wide diagonal cracks and substantial previous damage. *Response 2000*™ provided the best correlation with experimental results, while AASHTO-MCFT produced slightly conservative capacity estimations.

Curves to predict LCF life were developed based on beam stresses and observed cumulative damage after repeated cycles. Separate curves were made for girder sections of varying stirrup spacing; however, additional characterization of beam behavior during LCF may provide a generalized prediction tool of LCF life.

For bridge elements with small aspect ratios such as bent caps, AASHTO-MCFT and *Response 2000*™ predicted low capacity compared with load effects. In the analytical methods, the estimated shear capacity of the bent caps was limited by the treatment of the steel capacity and anchorage of the flexural steel at the bent column locations. More refined methods and models are required to better predict the capacity of bent caps.

Reliability Assessment

A reliability assessment methodology was developed to allow transportation personnel to rationally establish load restrictions, prioritize bridges for replacement or repair, and identify specific segments of bridges requiring repair. The methodology integrated the analysis from the field and laboratory testing with Oregon-specific truck loading, generated from weigh-in-motion (WIM) data. A technique was developed for calculating a reliability index (β) for each critical section of a girder by comparing the maximum operating forces in the section with the estimated capacity of the section and incorporating the inherent variability of the capacity estimate. The girder location with the smallest reliability index controls the capacity of the bridge.

After applying the reliability assessment methodology to a set of bridges to calibrate β, a minimum β can be selected for Oregon's RCDG bridges that represents an acceptable level of risk. A LCF evaluation is included in the assessment to determine whether cumulative damage from cyclic loading is a factor. After applying the assessment method to a series of bridges, the LCF evaluation may be eliminated if experience shows that LCF is clearly inconsequential.

Current limitations are described, including the impact of skew, temperature and shrinkage effects on capacity, as well as serious stem-flange interface cracking. There are also limitations in predicting the capacity of bent caps. Finally, recommendations are made for implementing the assessment methodology.